Living with a Star Targeted Research and Technology (LWS TR&T)

Draft Science Focused Science Topics (May 28, 2016)

Released for Community Comment

Note to the community from the LWS TR&T Steering Committee

Dear Colleagues,

This spring, we solicited your input for LWS Focused Science Topics for the ROSES 2017 Announcement of Opportunity and the response was amazing. We received 57 topics from all areas of Heliophysics and many comments. We are thrilled with your response.

We met in mid-May to carefully review all of these community suggested science topics, keeping in mind the overall Living with a Star goals and the TR&T Strategic Science Areas (SSAs). Based on all of this, we have prepared a draft set of 13 topics, appended here for your inspection and comment. We considered all submitted topics very carefully and created Focused Science Topics that include as much of this input as possible.

Please keep in mind that these are draft topics. We are now soliciting community feedback on these draft topics, as the next, critical stage of this year's process of generating science topics.

All of these draft topics will be posted on our website shortly, with input boxes for comments and feedback on each individual topic, as well as on the overall process. Once the feedback site is up and running, we will keep it open for at least six weeks, or until July 18 (the Monday following the SHINE meeting), whichever is later. The topics will be presented both as posters and as LWS TR&T town hall discussions during the SPD, CEDAR/GEM, and SHINE meetings to expose them to as much community input as possible.

After this comment period closes, the committee will meet again to review the community feedback on the topics and, based on this feedback and on the LWS and TR&T goals, to finalize the topics for presentation to the NAC Heliophysics Subcommittee, and via that subcommittee, to NASA Headquarters.

We look forward to your feedback on these draft topics.

Sincerely,

Mark Linton, co-chair

Eftyhia Zesta, co-chair

On behalf of the LWS TR&T Steering Committee

Mid-latitude and Equatorial Dynamics of the Ionosphere-Thermosphere System

Target Description:

It is well known that heating occurs first at high latitudes during magnetic storms. Energy is transferred from the magnetosphere to the ionosphere-thermosphere (I-T) through Joule heating and particle precipitation. Equally well known are the dramatic positive and negative ionospheric storm effects that undoubtedly result from this input and the complex IT interactions. However, we do not understand how this energy and dynamics are transferred to mid- and equatorial latitudes to form the plasma density and total electron content (TEC) distribution observed there as well as irregularities/scintillation. To date, much of what is known about mid-, low- and equatorial latitude electrodynamics is based on observations of a handful of incoherent scatter radars and from a limited longitudinal coverage. It is not surprising that I-T responses observed recently by satellites such as C/NOFS and recent ground instrumentation have been unpredictable and unexpected, such as significant longitudinal variability, which becomes the barrier for the ongoing global density structure modeling effort to improve the TEC and scintillation forecasting capability.

There has been a lot of speculation on the possible causes of longitudinal electrodynamics variability, which includes: (a) the disturbance dynamo, which is the large-scale neutral wind system responsible for transferring energy from high to low latitudes and across the equator, and/or large scale atmospheric and ionospheric waves (TADs and TIDs) (b) the longitudinal difference in the neutral wind magnitude and direction, (c) the coupling between lower atmosphere and ionosphere (possibly source for non-migrating tides and localized gravity wave activity), (d) the longitudinal difference in the magnetic field inclination and magnitude. However, due to the uneven distribution of suitable ground-based instruments, these speculations have not been validated or confirmed. The longitudinal distributions of ground-based instruments are now getting better and can be utilized for the longitudinal electrodynamics observations and also for latitudinal transport and waves from high latitudes to equatorial latitudes.

Understanding the latitudinal energy transport to lower latitudes and the longitudinal variability of mid-, low-, and equatorial latitude electrodynamics is essential to the following LWS strategic science areas (SSA): SSA-4 Physics-based TEC Forecasting Capability, and SSA-5 Physics-based Scintillation Forecasting Capability, as well as SSA-2 Physics-based Satellite Drag Forecasting Capability.

This topic is timely as it will advance and solidify our current state of understanding and capability to forecast scintillation and TEC structure at low latitudes and prepare the research path for multiple upcoming missions (ICON, GOLD, COSMIC-2)

Goals and Measures of Success:

To expand and solidify our understanding of the physical sources that drive low latitude plasma density distribution and structure as recently observed and of how it affects scintillation and TEC variability. Up-to-date simulation results should be compared with pertinent observations to quantify both our success level and the gaps in our understanding.

Types of Investigations:

We seek investigations that will take advantage of all recent deployment of mid-, low-, and equatorial latitude ground instrumentation of all kinds, and historical and ongoing observations from ground and space in combination with empirical and physics based models. Data assimilation techniques are also encouraged. Selected investigations should address any or all of the following scientific questions:

1. What is the mid-, low-, and equatorial latitude structure, particularly during geomagnetically active periods
2. How does the disturbance dynamo contribute to transferring energy from high to low latitudes and across the equator
3. What is the role of TIDs and TADs
4. How does the longitudinal difference in the neutral wind magnitude and direction affect longitudinal structure and scintillation
5. How does the coupling between lower atmosphere and ionosphere (possibly source for non-migrating tides and localized gravity wave activity) contribute and
6. What is the role of the longitudinal difference in the magnetic field inclination and magnitude.

Origins, Acceleration and Evolution of the Solar Wind

Target Description:
The supersonic, super-Alfvenic solar wind arises from the expansion of the million-Kelvin solar corona created by heating processes that are far from being understood. In-situ turbulence observed within the solar wind has a dissipation range, which is direct evidence of ongoing turbulent heating believed to operate throughout the heliosphere from the low corona out to the heliosheath. The Sun's subsurface convection powers all its mass loss and produces produces magnetic fields, creates flares through magnetic reconnection, drives coronal mass ejections, Alfvén waves, ion–cyclotron waves, and the various turbulent processes that evolve throughout the heliosphere. Understanding the origin, acceleration and evolution of the solar wind is critical for virtually predicting all forms of space weather. This directly relates to Strategic Science Area 0, which focuses on physics-based understanding enabling forecast capabilities of the variability of solar magnetic fields and particles.

This FST focuses on exploring the (many facets of) physical processes involved in the heliosphere's origin and evolution: the sources of different wind types and their connection to different coronal structures, the micro-physics of distribution functions and their anisotropies and various nonthermal characteristics, the role of turbulence and wave-particle interactions in heating and acceleration, the energization associated with structures, such as shocks, current sheets and/or magnetic reconnection. What specific observables can be derived from models? Furthermore, in preparation for the decade of inner heliospheric and coronal exploration with Solar Orbiter and Solar Probe Plus, what fundamental observations should drive theoretical developments?

Goals and Measures of Success:
The goal of this FST is develop metrics for testing various models of solar wind through comparison to an array of in situ and remote observations. Direct observations across a range of scales in time and space can be used to determine how turbulence evolves and dissipates, how the solar wind is heated in the low corona, how charge-states and elemental abundances in the solar wind are determined, how electrons and proton distributions transmit energy across different regions of the corona and through the transition region, and how nano-flares and magnetic reconnection transfer stored electromagnetic energy into particle distributions. Future observations will likely transform our understanding of solar wind origins and acceleration. In preparation, it is essential that we as a community define the array of models that need to be tested, and establish the specific metrics used to discriminate among them. This will allow future observations to be used efficiently to help in the development of new predictive models that take into account the array of observations that constrain different components of the solar wind.

Types of Investigations:
The nature of this research effort requires the interdisciplinary combination of observational, theoretical, and numerical studies, and focuses on the following subtopics:

- Role of waves and/or turbulence
- Role of reconnection
- Role/importance of electron physics (Topic 18)

- Role of minor ions
- Role of non-maxwellian distribution functions
- Role of nano-flares (Topic 35)
- Constraints from charge state and elemental composition
- Constraints on mass flux, solar wind power and relationship to the magnetic field
- Evolution of solar wind properties through the solar cycle

Studies within this program will combine theoretical, numerical, and observational methods. The successful outcome of each research effort will rely on high-quality data analyses from past and present missions – such as Helios 1 and 2, Wind, ACE, Ulysses, STEREO, SOHO, DSCOVR, etc. – to facilitate the robust comparison and constraint of models with measurements, and on high-performance computing to facilitate the multi-scale modeling activities.

Focus on Enabling Predictability and Interaction with User Communities:
The driving motivation of this FST is to advance our understanding of the origins, acceleration and evolution of the solar wind, to identify observational metrics that test solar wind models and to develop the understanding needed for predictive solar wind models. The FST should demonstrate how the expected advances will be relevant to user needs (for example, NOAA/SWPC).

Individual proposals should identify how they will contribute to the FST and aid with development to enable predictive understanding, observationally based metrics and model validation. Proposed investigations should outline the methodologies for enabling the goals, and the data sources and metrics to be used to monitor their progress. Successful investigation teams are expected to provide with their annual reports a description of their progress towards one or multiple goals associated with the FST. The complete FST team should synthesize results into a list of competing solar wind models, and their success or failure with respect to the array of observational metrics and specific validation tests that are generated across the team.

Ion Circulation and Effects on the Magnetosphere and Magnetosphere - Ionosphere Coupling

Target Description:

Accurate knowledge and understanding of the magnetospheric composition is critical for understanding the space environment. Plasma of ionospheric origin is seen to dominate the ring current energy density during geomagnetic storms. The heavy ions and O+ ions in particular affect the radiation belt population through controlling the growth and interaction of radiation belt particles with EMIC waves. They are a substantial constituent of the ring current and plasma sheet especially during extreme geomagnetic storms. O+ can also affect the global Solar Wind – Magnetosphere coupling by quenching dayside reconnection rates as well as global magnetospheric convection, and on the night side affecting location and recurrence of reconnection and associated instabilities. Thus the ion composition, and in particular O+, play an important role in understanding geomagnetic variability (SSA-1) and the radiation environment (SSA-6).

Despite these wide reaching consequences for the space environment, understanding and modeling of the magnetospheric composition and all of the associated feedback mechanisms is an extremely challenging task, and an important issue for space weather models. While some progress has been achieved in understanding how O+ is energized and transported from the central plasma sheet to the ring current, the source and transport mechanisms in the ionosphere and to the magnetosphere are less understood largely because they are a result of a complex interplay between the solar wind, magnetospheric activity and the ionosphere. To complete our understanding of the O+ cycle through geospace a better understanding of the transport mechanisms is essential. Mechanisms include transport of ionospheric material from mid- to high-latitudes, potentially through the cusp region and polar cap, cusp outflow stimulated by precipitation and poynting flux (in turn stimulated by solar wind variability), outflow from the auroral regions, outflow directly from sub-auroral latitudes leading to the warm plasmaspheric cloak.

This topic focuses on how and when ions and O+ in particular is supplied to the magnetosphere and where it is available for energization. Newly available data from the Van Allen Probes and MMS satellites sampling both inner and outer magnetosphere, and covering eV to MeV energies provides an unprecedented opportunity to determine the accumulation and energization processes of O+ ions throughout the magnetosphere during geomagnetic storms. A number of other currently-operating spacecraft, as well as new missions soon to launch, support these topics as well, forming a comprehensive suite of observations that can support studies of conductivity, as well as (in many cases) interhemispheric effects. In addition, global models and computational capabilities have reached the level of maturity allowing taking full advantage of the available data.

Goals and Measures of Success:

- A quantitative understanding of the relative roles of different mechanisms and the resulting magnetospheric distribution.

Types of Investigations:
As there is currently an FST which is dedicated to a portion of this topic considering how O+ is energized and transported through the transition region from the plasma sheet to the ring current, proposed investigations should focus on other aspects of the heavy ion circulation throughout the magnetosphere while being aware of, incorporate, and work with the currently funded FST. Suggested types of investigations include:

- Data analysis seeking to characterize ionospheric and magnetospheric processes that directly or indirectly are critical for the supply of O+ to the magnetosphere. This includes their dependence on solar drivers, seasonal changes, and magnetospheric drivers.
- Data analysis that seeks to characterize the spatial and temporal distribution of O+ in the inner magnetosphere to the outer magnetosphere.
- Modeling seeking to understand and confirm the physical mechanisms that directly or indirectly are critical for the supply of O+ to the magnetosphere.

Toward a Systems Approach to Energetic Particle Acceleration and Transport on the Sun and in the Heliosphere

Target Description:

An understanding of the acceleration and transport of energetic electrons and ions on the Sun {Solar Energetic Particles, or SEPs) and in the heliosphere is central to predicting and mitigating space weather threats and advancing human exploration of space. While flare acceleration mechanisms on the Sun and CME-driven shock acceleration mechanisms in the heliosphere have been studied for many years, possible relationships between the two have only been appreciated relatively recently. For example, shocks may be present in flares due to reconnection outflows; and flares may play a role in high-energy SEP events, in contrast to the more widely-held view that large gradual SEP events are dominated by shocks at all energies. It has also been recognized that the coupling between flare acceleration and CME-shock acceleration is not one-way: recent high-sensitivity observations by the Fermi revealed gamma-rays associated with flares occurring up to ~40 degrees behind the solar limb and gamma-ray emission long after the flare X-ray and EUV emissions have subsided. Both revive the idea that CME-shock accelerated particles traveling back to the Sun to produce gamma-rays.

The exact physical relationship and relative importance of flare acceleration and CME-shock acceleration remain controversial. Nevertheless, significant progress has been made in understanding flare physics, CME shocks, and shock acceleration thanks to missions flown over the past decade - including RHESSI, Fermi, TRACE, SDO, SOHO, ACE, and STEREO – as well as progress on theoretical understanding. With anticipation growing for the Solar Probe Plus and Solar Orbiter missions it is appropriate and necessary to take a systems approach to the problem of solar energetic particle acceleration and transport as a means of advancing physics-based models and developing predictive capabilities.

Goals and Measures of Success:

The goal of this FST is to take a systems approach to understanding the acceleration and transport of solar energetic particles; to develop a detailed observational understanding of the properties of the source regions of solar energetic particles; to understand the composition and evolution of solar energetic particle populations in time and space; to identify the mechanisms by which impulsive energetic particle events or gradual events of large angular extent occur; to understand the relative roles of flares and CMEs in producing energetic particles as well as the underlying acceleration mechanisms; to understand the origin and distribution of seed particles; and to develop advanced systems-based models of the production and transport of solar energetic particles as precursors to predictive capabilities.

Investigations based on observational, theoretical, and/or modeling initiatives are expected to show clearly how they contribute to a broader understanding of the coupled physical processes that underpin the production and transport of solar energetic particles. Observational investigations must show how they lead to data or data products that may be assimilated by models. Theoretical investigations must lead to an understanding of the comparative importance of the coupled physical processes that contribute to the acceleration and transport of solar energetic particles. Modeling efforts should leverage progress in observations and theory to demonstrably improve our understanding of the timing, origin, and properties of solar energetic particles and their potential for affecting the near-Earth environment.

Types of Investigation:

- Determination of the relative importance of various particle acceleration mechanisms (e.g., magnetic reconnection, turbulence, and shocks), and particle transport mechanisms, in different physical scenarios, primarily with modeling approaches.
- Comparative studies of particle populations on the Sun inferred from their electromagnetic radiations and/or those detected in-situ.
- Determination of the origin and distribution of seed populations of SEPS, and investigation of the relative importance of contributions to the seed populations of SEPs, such as flare-accelerated particles escaping the Sun and/or relics of a previous CME.
- Investigation of CME evolution and shock formation/evolution and/or flare initiation and evolution in order to determine conditions leading to acceleration of SEPs.
- Investigation of the relative roles of flares and CME-driven shocks in the acceleration of energetic particles, as well as temporally and spatially extended gamma-ray events.
- Determination of the distribution of spectral and isotopic characteristics of SEPs, and characterization of the underlying causes for the the distinction between highly impulsive and gradual SEP events.

Focus on Enabling Predictability and Interaction with User Communities:
The strategic science area “Physics-based Solar Energetic Particle Forecasting Capability” (SSA-3) requires a fundamental understanding of the acceleration and transport of solar energetic particles. This FST aims to advance this understanding through observational, theoretical, and modeling initiatives that result in improved understanding of the relevant mechanisms, data products that may be assimilated into models, and models that improve the predictability of the timing and origin of SEPs, ultimately informing SSA-6 (“Physics-based Radiation Environment Forecasting Capability”). An important component of the FST is to demonstrate relevance to user needs (for example, NASA/SRAG or NOAA/SWPC). Individual proposals should identify how they will contribute to the FST and aid with development of a predictive capability.

Coupling Between Different Plasma Populations by Means of Waves

Target Description:
Plasma waves play an important role in the dynamics of different magnetospheric plasma populations. Ultra Low Frequency (ULF) waves are responsible for the radial diffusive transport, Very Low Frequency (VLF) and Extremely Low Frequency (ELF) waves inside the plasmasphere provide pitch angle scattering and loss of particles and VLF waves outside of the plasmasphere can provide both loss of particles due to pitch angle scattering and acceleration due to energy diffusion. Waves also provide mechanisms by which different plasma populations can interact with each other. For example, ring current ions generate Electromagnetic Ion Cyclotron (EMIC) and chorus waves that can energize and scatter radiation belt electrons. Background plasma density and ion composition play an important role in modulating the generation of waves and wave-particle interactions. High-fidelity multi-point in-situ measurements of the magnetic and electric fields, electron and ion fluxes, and ion composition from the Van Allen Probes, MMS, THEMIS, and Cluster spacecraft, amongst other resources, provide a unique and timely opportunity to quantify the significance of each mechanism as a function of solar wind and geomagnetic conditions. This FST is most relevant to SSA-0 (Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and Inputs to Earth's Atmosphere), SSA-1 (Geomagnetic Variability), and SSA-6 (Radiation Environment).

Goals and Measures of Success:
Plasma waves play an important role in the dynamics of various inner magnetospheric plasma populations. The main goal of this investigation is to understand and quantify how different plasma populations (including thermal plasmas, the ring current, heavy ions, and radiation belt electrons) influence each other. This investigation will help quantify the dynamic evolution of different particle populations and will improve the forecasting capabilities of current and future computational models. This topic will help us understand particle dynamics and its dependence on solar wind conditions.

Types of Investigations:
Development of empirical models for plasma population dynamics.
Theoretical studies of wave-particle interactions.
Modeling studies combining the dynamics of various plasma populations coupled by means of wave-particle interactions.
Validation of the models and theoretical predictions via comparison with multipoint in-situ observations.

Probabilistic Forecasting and Physical Understanding of Extreme Events

Target Description:

Strategic Science Area SSA-0 focuses on physics-based understanding enabling forecast capabilities for the events driven by the variability of solar magnetic fields. All strategic science areas rely in some way on the development of predictive understanding emerging from SSA-0. Extreme solar events represent an important example of such phenomena that present significant potential hazards associated with abrupt increases in solar energetic particle radiation and geospace superstorms. Rarely occurring extreme events generate X-rays and solar radio bursts, accelerate solar energetic particles to relativistic velocities within minutes and cause powerful coronal mass ejections. At Earth, the associated changes in the space environment can cause detrimental effects to the electricity grid. In space extreme events can damage satellites and avionics. Extreme events also cause increases in radiation levels at aviation altitudes that can affect airline passengers and crews. Additional effects of extreme events include disruptions of satellite navigation systems, mobile telephones, and a host of additional effects for Earth and satellite-based technologies. Extreme solar events have consequently been identified as a risk to the world economy and society.

Several examples of extreme event effects include the 1989 collapse of part of the Canadian electricity grid. A superstorm which occurred in 1859, now referred to as the ‘Carrington event’ is the largest for which we have measurements; and even in this case the measurements are limited to perturbations of the geomagnetic field. An event in 1956 is the highest recorded for atmospheric radiation with August 1972, October 1989 and October 2003 the highest recorded radiation events measured on spacecraft. How often superstorms occur, what their probabilities are, how they are generated and whether the events listed above are representative of the long-term risk are not known. The general consensus is that a solar superstorm is inevitable, a matter not of ‘if’ but ‘when?’

The purpose of this FST is to develop methods for assessing the probability of extreme events, to develop a consensus record of extreme events, and to develop observational proxies and physical understanding that can be used for probabilistic forecasting in the future. The FST calls for a concerted effort to study extreme events observationally, theoretically and using simulations in order to identify potential causes and possible precursors, with an emphasis on development of physical understanding that may be used for probabilistic forecasting.

Goals and Measures of Success:

The goal of this FST is multifold: to develop a consensus record of extreme events, to advance and develop models of extreme events, to validate these models via comparison to satellite data, ground-based data and historical records of these extreme events, to develop observational precursors, and to develop probabilistic forecasting methods for extreme events. Measures of success are (1) the development of metrics to test or quantify the success of extreme event models, (2) the development of observational precursors that can be used to quantify the likelihood of an impending extreme event, (3) the development of methodologies for probabilistic forecasting, (4) the examination of historic datasets and satellite data that can be used to assess extreme events that may have occurred in the past, and (5) the development of a consensus record of extreme events.

Types of Investigations:

- Studies that use historical records (e.g., ice core, 36Cl data, and 14C data in tree rings), ground based data (e.g., magnetometer and auroral observations) and satellite data to identify a consensus record of extreme events for comparison with results of models.
- Advancement and development of models to understand physical origins of extreme events.
- Validation of extreme event models, both existing and newly developed under this FST, against consensus records of extreme events.
- Identification of potential observational precursors that may be used in the future for event forecasts.
- Application of statistical methods for probabilistic forecasting based on specific observational precursors.

Focus on Enabling Predictability and Interaction with User Communities:

The driving motivation of this FST is to advance substantially our physical understanding of extreme events, to identify observational precursors, and to develop an understanding of the probabilities that such events will arise in the future. The FST should demonstrate how the expected advances will be relevant to user needs (for example, NASA/SRAG or NOAA/SWPC). Individual proposals should identify how they will contribute to the FST and aid with development to enable predictive understanding, observationally based forecasting and probabilistic understanding. Proposed investigations should outline their methodologies for enabling these goals, and the data sources and metrics to be used to monitor their progress. Successful investigation teams are expected to provide, with their annual reports, a description of their progress towards one or multiple goals associated with the FST.

Understanding Physical Processes in the Magnetosphere--Ionosphere / Thermosphere / Mesosphere System During Extreme Events

Target Description:

Detailed observations of heliospheric processes during superstorms are rather limited, and statistics is sparse. Evidence that geomagnetic storms can potentially be much stronger than that observed during the space age comes from historical observations of the solar storm in 1989, known as Carrington storm, and recent observations of the very powerful Coronal Mass Ejections (CME) that occurred in July 2012, that largely missed the Earth. Understanding the effects of superstorms and the strongest (e.g., 1 in 100 years) space weather events is a key component of the National Space Weather Action Plan. Such an understanding is required to develop mitigation strategies for worst case Geomagnetically Induced Currents (GIC), spacecraft charging, communication outages and navigation error scenarios. Understanding the coupling processes that occur under extreme conditions presents a challenge, as these processes may be very different than those under the more typical conditions for which existing physics-based models were developed. Saturation processes or nonlinear responses of the systems during extreme driving may preclude extending empirical parameterizations to the more extreme values for drivers that occur during such events. Using available observations of superstorms and historical records of extreme events, this FST will conduct focused investigations of key physical processes needed to extend modeling capabilities to the conditions that occur during extreme events. This proposed topic is relevant to nearly all of the Strategic Science Areas (SSAs).

Measures of success:

The efforts of this FTS will be targeted at filling critical gaps in our understanding of the system dynamics that occur during the extreme events. This FST will improve our ability to model superstorms and Carrington-type storms and improve our ability to predict the consequences of the extreme events. The advances made by this FST may feed into a future long-term strategic capability topic on the integrated magnetospheric response to superstorms.

Types of investigations:

- Theoretical and modeling studies focused on understanding the physics of solar wind-magnetosphere interaction changes from normal times to superstorms/extreme events.

- Studies concerning the response of currents, radiation belt particle fluxes, and magnetospheric electric and magnetic fields to extreme driving.

- Multipoint and multi-instrument observations of superstorms.

- Development and validation of simulations that can accurately represent the extreme responses that occur in the magnetosphere and ionosphere during superstorms and Carrington-type storms.

- Application of the extreme value theory to understand the extreme behavior of heliophysics systems and making predictions.

Understanding the Impact of Thermospheric Structure and Dynamics on Orbital Drag

Target Description:

Operators of Low Earth Orbit (LEO) spacecraft face a constant operational challenge due to variable atmospheric expansion and contraction producing non-constant drag forces on a spacecraft that alter its attitude and orbit. The satellite drag force is dependent on a number of factors, including the atmospheric density, the ballistic coefficient, and the relative speed of the satellite within the atmosphere. LEO situational awareness requires continuous precise orbit determination, conjunction assessment, and collision avoidance actions that involve not only the spacecraft response to atmospheric drag but also the drag response of all the other space objects in LEO, especially debris. In LEO, atmospheric drag is the largest contributor to errors in orbit determination and is associated with problems related to satellite tracking, collision avoidance, and re-entry prediction. Thus, improved estimates of atmospheric drag on LEO spacecraft and space objects will positively impact the operations and performance of these critical space assets. Typical estimates of the atmospheric density 1-sigma error at 400 km are on the order of 8-20%; yet these errors can be a factor of 2 or 4 during geomagnetic storm periods. These uncertainties become cumulative when trying to predict an object's future position. Atmospheric drag in LEO is highly dependent on the state of the neutral gas population that makes up the Earth's thermosphere region (100-1000 km altitude), especially the mass density and wind. Space weather events can alter the thermospheric state and produce variability that can exceed an order of magnitude. Furthermore, most of the geospace energy input to the atmosphere comes through high latitudes with significant mesoscale structure and can take several hours before the heating is globalized. The current understanding is that most of the energy transfer to all latitudes happens through waves, TADs and TIDs. This means that different LEO space objects can suffer highly variable drag depending on their orbital characteristics.

Although orbit prediction is mainly dependent upon the neutral density, the drag along the orbit is also dependent on the in-track and cross-track winds, traveling atmospheric disturbances (TADs), and atmospheric composition. The increase of carbon dioxide in the lower thermosphere, for example, appears to cause a cooler thermosphere during solar minimum conditions, thus helps the thermosphere to collapse, decreases its density, and lengthens the lifetime of orbiting debris. Forcings from the lower atmosphere as well as from the high-latitude region play a role in the day-to-day variability in the equatorial and mid-latitude ionosphere. Scintillation, ionospheric bubbles and ionospheric irregularities are related aspects of the manifestation of the coupling of the ionosphere and the atmosphere. Changes in the neutral upper atmosphere can also affect the ionospheric density distribution and total electron content, especially during geomagnetically active times. Understanding thermospheric composition changes is crucial to predicting negative ionospheric storm effects and better atmospheric density and wind models are needed, especially during geomagnetic storm periods.

Connections between models and observations, data assimilation methodologies, and high-performance computing all play relevant roles in improving satellite orbit determination. Investigations related to magnetosphere-ionosphere-thermosphere coupling, atmospheric and ionospheric disturbances during geomagnetic storms, meso and small-scale structuring, all contribute to this topic.

This topic is focused on SSA-2 (Satellite Drag) and aims to understand the physical causes for the main atmospheric parameters (mass density and winds) that are the primary error contributors to atmospheric drag. With the upcoming development of the Geospace Dynamics Constellation (GDC) and DYNAMIC missions, as well as the soon-to-be-launched ICON and GOLD missions, this topic is very timely. A better understanding of existing datasets and the improvement of models will strongly benefit these upcoming missions. This topic will also benefit by the parallel-in-topi new AFOSR MURI.

Types of investigations:

We seek studies that will use available observations to determine the effect of different input parameters and scale sizes on atmospheric density. Determine the time-scales of thermospheric responses both locally and globally, and focus model-observation comparisons on all those time scales, from minutes, to orbit-averaged, to multi-hr and daily. Cooling rates of the heated thermosphere based on composition changes and wind dynamics should also be explored and improved. Empirical and physics-based model results need to be compared and validated by observations. Coupled models and data assimilation schemes should also be considered, compared and validated. This FST does not provide for the development of new models, since the ultimate goal is focus and clarify our present understanding and to identify and quantify the gaps in our existing understanding, and specification and forecasting capabilities. However, funding for key small improvements of models and techniques can be requested to aid the analysis.

Proposed studies should focus on the following science questions:

- What existing and future observations will improve the characterization of neutral density structure and magnitude?
- How do temporal changes in the sources of heating and thermal expansion lead to specific density and wind structure?
- What are the physical processes driving the response of density and winds?
- How can thermospheric cooling during solar minimum periods be predicted?
- How are temperature and composition altered leading to changes in mass density structure?
- What are TID and TAD temporal and spatial characteristics, sources, and effects on TEC structure and mass density? How do they affect the day-to-day variability of mass density.
- What is the relation of neutral winds and composition changes that lead to mass density changes?

Solar Magnetic Inputs to Coronal and Heliospheric Models

Target Description:

One of the primary goals of the LWS program is to achieve a quantitative understanding of how the Sun influences the Earth's magnetic environment. A key aspect of understanding this interaction is the ability to quantitatively describe – and ultimately predict - the global solar corona and inner heliosphere. This proposed topic is essential to nearly all of the Strategic Science Areas (SSAs), but is especially important for SSA-0 (Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and Inputs to Earth's Atmosphere), SSA-1 (Geomagnetic Variability), SSA-3 (Solar Energetic Particle), and SSA-6 (Radiation Environment). A crucial input to models of the global solar corona and of the solar wind, whether they be empirical or physics-based, is the magnetic field at the solar surface. Models frequently use synoptic magnetic maps, which are built up from individual full-disk photospheric magnetograms taken over the course of a solar rotation. These synoptic maps can be developed from a number of ground- and space-based observatories, including, but not limited to: GONG, SOLIS, MDI, and HMI. Future investigations, including COSMO and Solar Probe Plus (SPP), will provide even richer, more complex measurements in the near future.

Current global models of the solar corona and inner heliosphere are driven by such observations, but are severely hampered by limitations of the observations and in the analysis of these observations. In particularly, synoptic maps suffer from a number of problems and limitations. First, they are not "synchronic" maps, that is, instantaneous snapshots of the global photospheric field at one time, which is what the global models require. Second, these maps often differ substantially from one observatory to the next and accurate inter-calibration is complicated. Third, the polar regions, which make a significant contribution to the open flux observed in the heliosphere, are seasonally obscured and poorly – if at all – observed. Fourth, differential rotation effects are only sometimes incorporated, and then, not systematically from one observatory to the next. Fifth, line-of-sight magnetograms (rather than the potentially available vector measurements) are used to reconstruct the radial photospheric field. Ideally, time sequences of global maps that smoothly assimilate new data (including far-side measurements) would be available to drive global models and provide a real-time forecast of the state of the heliosphere.

With the availability of almost six years' worth of full disk vector magnetograms at high time cadence from the HMI instrument on board SDO and the launch of SPP in two years, a rigorous assessment of the use of magnetograms and magnetic maps in quantitative models of the corona and solar wind is both timely and necessary. To make a significant breakthrough, however, will require a team approach, including photospheric magnetic field observers, flux-evolution modelers, and corona/solar wind modelers.

Goals and Measures of Success:

The goal of this focus team will be to obtain a quantitative understanding of the best use of magnetogram-derived maps for the purposes of predicting the global state of the solar corona and of the solar wind parameters (e.g., solar wind speed, IMF polarity, open magnetic flux, plasma parameters, etc.). While the assessment /analysis of individual magnetograms would be an appropriate component of this effort, the focus would be on the production of the most accurate maps of the Sun’s global magnetic field (as opposed to, say, the surface magnetic field in an active region). Measures of success would be:

- A standard inter-calibration for photospheric magnetic maps from different sources.
- Accurate estimates of the Sun’s polar magnetic fields during different seasons and parts of the solar cycle.
- The ability to characterize the photospheric magnetic field on the Sun as a function of time.
- Improvements to the accuracy of coronal and solar wind models for both real time descriptions and for forecasts.

Types of investigations:

- Studies that quantitatively calibrate magnetograms from NASA missions (e.g., SOHO/MDI and SDO/HMI) with measurements from ground-based observatories to obtain a best estimate of the Sun’s magnetic field.
- Studies that quantitatively characterize and assess the accuracy of different techniques for producing photospheric magnetic maps, including estimates of the Sun’s polar magnetic field and the use of synchronic or synoptic maps.
- Studies that use vector magnetograph data to improve the estimate of the Sun’s global magnetic field.
- Studies that quantitatively describe the evolution of the Sun’s surface magnetic field via flux evolution models which, for example, assimilate new magnetograms into real-time descriptions of the state of Sun’s magnetic field, incorporate estimates of the Sun’s field from far-side images, and / or incorporate differential rotation and dispersion into predictive models of this evolution.
- Studies that quantitatively assess the impact of extrapolation techniques (e.g., potential versus nonlinear-force-free versus magnetohydrodynamical) on our ability to model observed coronal structures and the observed temporal evolution of the solar wind.

Focus on Enabling Predictability and Interaction with User Communities:

An important component of the FST is to demonstrate relevance to user needs. For example, measurements of the Sun’s global magnetic field are presently the primary data input for the background model of the solar wind used at NOAA SWPC. Individual proposals should identify how they will contribute to the FST and improve magnetic data that can eventually be used in user/operational mode

Understanding the Response of Magnetospheric Plasma Populations to Solar Wind Structures

Target Description:

Plasma populations govern space weather conditions within the Earth's magnetosphere. Energetic particles cause single-event upsets and deep dielectric charging in spacecraft electronics and may be harmful to humans in space. While magnetospheric dynamics is driven by the solar wind, the non-linear response of the magnetospheric populations to different driving conditions is still poorly quantified. Solar wind can change the locations of the magnetopause and plasmapause, can change the configuration of the global magnetic and electric fields and can drive the generation of Ultra Low Frequency, Very Low Frequency, and Extremely Low Frequency waves that can interact with particles. Understanding and predicting when and where radiation effects related to space weather may occur requires detailed knowledge of the how particle radiation is driven by the solar wind. The objectives of this FST center upon specifying the response of magnetospheric thermal, ring current, and radiation belt particle populations to solar wind (and foreshock-modified solar wind) structures such as high speed streams (HSS), coronal mass ejections (CMEs), and interplanetary shocks. This FST is relevant to LWS TR&T Strategic Science Areas (SSA's): SSA-0: Solar electromagnetic, energetic particle, and plasma outputs driving the solar system environment and inputs to Earth's atmosphere; SSA-1: Geomagnetic Variability; and SSA-6: Radiation Environment.

Goals and Measures of Success:

Improved empirical models for the magnetospheric plasma environment as a function of solar wind and geomagnetic conditions.

Improved first principle models capable of predicting the time-dependent response of magnetospheric plasma populations to varying solar wind conditions.

Validation of these models, and specification of intrinsic errors.

Types of Investigations:

Development of the quantitative models for magnetospheric plasma populations demands the coordinated research of investigators with access to multipoint ground-based and spacecraft observations of magnetospheric and solar wind conditions, as well as global numerical simulations. Investigations will focus on understanding how particular structures in the solar wind determine the spatial and temporal evolution of the magnetospheric plasma populations. Illustrative case studies, empirical models, investigations involving machine learning, and the development of global simulations capable of assimilating both in situ and remote observations are encouraged.

Heliospheric and Magnetospheric Energetic Precipitation to the Atmosphere and Its Consequences

Target Description:
Energetic particle precipitation has a significant impact on the coupled magnetosphere-ionosphere system, extending down to the mesosphere - lower thermosphere domain as well. In recent years, we have significantly improved our understanding of the acceleration mechanisms while loss mechanisms and effects associated with the loss to the atmosphere and ionosphere remain to be poorly understood. Electron precipitation above ~keV and proton precipitation above ~100 keV ionize the D and lower E regions of the ionosphere and contribute directly and indirectly to the production of NOx and HOx constituents in the upper atmosphere. The ionization, complicated chemistry, and precise effects of these products is nuanced. One difficulty in understanding and projecting the future states of the atmosphere comes from our inability to identify and isolate the signals from external forcing and different feedback processes. These feedback processes include the intermediate region of M-LT to the Sun and the lower atmosphere as well as the feedback from the particle precipitation back to the magnetosphere. But before we can look at these higher order effects we first need to better understand, quantify and ultimately forecast the input energy spectra and the spatiotemporal dynamics that impact the atmosphere. The aggregate energy input into the Magnetosphere-Ionosphere-Thermosphere system is not known at this point, nor is it known how this varies with latitude and longitude, with geomagnetic activity, or with solar cycle. This science topic can be investigated comprehensively using both space- and ground-based measurements or kinetic modelling. How heliospheric and magnetospheric energetic particles impact the ionosphere-atmosphere system is still a vast open question in the field, and this final portion of the full Sun-Earth system is key to understanding the entire energy pathway leading to advancing the knowledge relevant to SSA-0 (We can make direct headway on this topic by really quantifying the precipitating flux and utilizing the current and future measurements to discern the effect this precipitation has on the atmosphere.), SSA-2 (as the high-energy end of this spectrum, which can affect satellite drag, has not been sufficiently investigated in the past.), SSA-3 (This topic addresses SEPs directly, in the context of SEP direct access to Earth's atmosphere, particularly in the polar cap.), and SSA-6 (This topic aims to directly study the precipitating component of the radiation environment, and employ modeling methods to determine the effects on the atmosphere directly.) With observations from Van Allen Probes, the upcoming ERG mission, an increasing number of CubeSat and SmallSat focusing on measuring precipitating fluxes, and wealth of ground based data sets and current modeling efforts, now is arguably the best chance we have to really bring closure to this science topic.

Goals and Measures of success:
The primary goal of this FST is to quantify What are the long- and short-term variations in the energetic particle precipitating spectrum. This FST should lead to a better understanding of how these precipitation events are affected by geomagnetic activity and solar cycle, ultimately leading to understanding and forecasting of the region affected by this ionization, provide inputs to atmospheric chemistry models, determine the size and temporal scales of the regions affected, as well as how this changes with the intensity level of particle precipitation.

Types of Investigations:

- Theoretical, empirical, and modelling studies focused on predicting particle precipitation to the atmosphere.
- Multipoint and multi-instrument observations of particle precipitation during periods of geomagnetic activity specifically looking at the precipitated energy spectra and flux as well as the MLT - L or equivalently the Latitudinal and longitudinal extend of the precipitation.
- Development and validation of simulations that can accurately represent particle precipitation to the atmosphere and its dependence on geomagnetic activity.
- Studies which consider the relative importance of different loss mechanisms to the upper atmosphere.

Understanding The Onset of Major Solar Eruptions

Target Description: The LWS program has the overarching goal to achieve a quantitative understanding of how the Sun influences the Earth's environment. A key aspect of understanding this interaction is the ability to quantitatively describe – and ultimately predict - the occurrence of major solar eruptions. This proposed topic is essential to nearly all of the LWS Strategic Science Areas (SSAs). For example, Solar Energetic Particle (SEP) events generated by flares and Coronal Mass Ejections increase radiation hazards throughout the solar system and adversely impact our space- and ground-based assets. The initial particles can arrive in minutes to hours after an eruption on the Sun.

A key difficulty in achieving the goals of SSA-3 (probabilistic prediction of the spectral intensity of SEP events, and increased time periods for all-clear forecasts) is forecasting the likelihood of a major eruption from active region(s) on the Sun, hours to days prior to the event. Present-day forecasts are empirical. For example, NOAA/SWPC currently relies on qualitative assessments of sunspot groups to produce a 24, 48, and 72 hour forecasts. There are statistical methods that could potentially improve these forecasts based on characterizion of prior flaring, surface solar magnetic field properties derived from magnetograms, etc. However, even such techniques typically have little theoretical or modeling insight incorporated into their methodologies.

There has been significant theoretical, modeling and observational work on the eruptive properties of solar magnetic fields, as evidenced by previous LWS Focused Science Teams (FSTs). However, it appears we are still many years away from an entirely first principles approach for predicting major eruptions. The goal of this FST is to directly combine insights from theory, modeling, and observations to improve probabilistic forecasts of major solar eruptions required by the user community.

Goals and Measures of Success:

The goal of this science topic will be to obtain a quantitative understanding of observational and modeling signatures of magnetic flux emergence, the interaction of the emerging flux with existing structure, and the degree of non-potentiality in the atmosphere leading to major solar eruptions. This requires studies of local and global-scale phenomena as ably demonstrated by the observations of the Solar Dynamics Observatory over the past six years. Some measures of success would be:

- The ability to integrate numerical and observational studies across the breadth of temporal and spatial scales to better understand major eruptions.
- The ability to differentiate between minor and major storm eruptions.
- The ability to robustly determine "all-clear" periods for major eruptions.
- Production of critical derived data products such as Poynting flux, helicity flux injection, and free energy build up from the observables with appropriate estimates of uncertainties.
- Identification of comprehensive, consistent, robust extrapolation methods involving magnetic field measurements in photosphere, chromosphere and corona to identify degrees of non-potentiality and the timescales on which it develops.

Types of investigations:

- Studies (Observational, theoretical, empirical, statistical and/or modeling) that identify signatures of stability and/or imminent eruption triggering and onset
- Studies which use these signatures to provide probabilistic forecasts of major solar eruptions:
    - Studies of the processes by which the emergence of magnetic flux energizes pre-eruptive active regions and / or triggers eruptions.
    - Studies that quantify the flux of magnetic energy stored, entering, or leaving solar active regions, and study how this relates to the triggering of eruptions
- Studies that identify signatures of stability and/or imminent eruption.
    - Studies of magnetic reconnection onset or other destabilization mechanisms, as related to eruption onset, throughout the solar atmosphere and across the broad range of scales presented therein.
    - Studies that relate inferred/measured quantities such as free magnetic energy, non-potentiality, helicity flux injection, and Poynting flux injection to the likelihood of a major event.

Focus on Enabling Predictability and Interaction with User Communities:

An important component of the FST is to demonstrate relevance to user needs, especially when designating storm onset, assessing all-clear periods, or differentiating between minor and major solar events. For example, an end user of this FST would be the operational group at NOAA/SWPC. Individual proposals should identify how they will contribute to the FST and improve understanding of major event onset and the physical properties of those events that can eventually be transitioned to user/operational models.

Understanding Ionosphere-Thermosphere (IT) responses to high-latitude processes and Magnetospheric energy input

Target Description:

The ionosphere is electro-dynamically coupled with the magnetosphere from above, but also co-located and mechanically coupled with the dense neutral atmosphere. While the major energy source for the IT system is solar EUV flux, during geomagnetically active times, like storms, magnetospheric energy input can be equally or even more important. The result can be transient but severe effects on the Earth environment, like communication disruptions, changes on orbital drag and the lifetime of LEO satellites and more. Magnetospheric energy input enters at high latitudes through complex, coupled processes. As a result electron density and thermospheric mass density at a given altitude are both spatially and temporally variable to magnetospheric energy input. Changes in the neutral upper atmosphere can affect a host of critical processes like ion-neutral drag coupling that governs the exchange of momentum and Joule heating rates, species-dependent chemistry and recombination rates that change the electrical conductivity of the ionosphere, altitude profile of precipitation absorption and ionization that affect ionospheric conductivity and MI coupling. Electron density profiles and TEC are similarly affected by high-latitude energy input. There is a need to understand the causes and consequences of this thermospheric mass density and TEC variations, which are critical to and not well captured by existing models but where data exist. There is a need to observationally establish meso-scale patterns of energy input and responses and advance the ability of models to capture the important missing physics. Better parameterizations are needed to dramatically improve our predictive capability for thermospheric density, particularly during periods of enhanced geomagnetic activity and even, though not exclusively, during extreme solar minimum conditions.

Open questions include:

- 1) how do magnetospheric energy inputs become processed to provide local, regional, or global changes in thermospheric density, electron content and TEC. For example, what are the effects of different scale sizes in energy inputs in terms of energy budget available to the IT system.
- 2) What are the effects of precipitation on the structure of ionospheric conductivity and neutral heating. For example soft electron precipitation vs Joule heating in producing cusp neutral upwelling, heating sources vs conductivity sources, the effect of secondary electrons, etc
- 3) What are the variations in thermospheric composition during geomagnetically active events, including neutral Helium, and how are they driven by various energy inputs; How does composition affect the IT responses, for example, negative vs positive ionospheric storms.
- 4) What are the mechanisms that drive thermospheric heating in the high and polar latitudes. For example, are recently shown polar heating during storms the result of Joule heating?

The focus of this topic is to improve the ability of models to capture the important missing physics and parameterizations needed to dramatically improve our predictive capability for TEC, electron density profiles and thermospheric density, particularly during periods of enhanced geomagnetic activity and even, though not exclusively, during extreme solar minimum conditions, for satellite drag applications and within the context of SSA-2: Physics-based satellite drag forecasting capability and SSA-4, Total Electron Content (TEC).

Goals and Measures of Success:

The primary goal of this FST is to promote understanding of neutral density variability, from the lower thermosphere well into the exosphere (>600 km), that result from high-latitude heating and cooling conditions. Comparisons of both empirical and physics-based models of the density during storms to existing in-situ and remote-sensed satellite density data is critical to evaluating the success of these models. Proposals should suggest metrics that can demonstrate reductions in density variability uncertainty and identify application paths.

Types of Investigations:

This solicitation seeks investigations that focus on the observational determination of different scale structures of energy inputs and IT responses at high latitudes as well as the improvement of empirical and/or physics-based IT and coupled models. Areas needing improvement will be found through comparison of modeled TEC, ionospheric density and neutral density with existing observations during geomagnetically active periods; this will help improve, verify and validate modeled density improvements. How models vary with different solar and magnetospheric inputs is a desired research area, including the use of spectral irradiances and spectral proxies or indices beyond F10.7 and geomagnetic indices beyond Ap. It is anticipated that model-data comparisons may lead toward nearer-term ensemble modeling and/or data assimilation techniques that may help quantify neutral density uncertainties.

Focus on Enabling Predictability and Interaction with User Communities:

Proposals in response to this solicitation are encouraged to understand and state user requirements for drag specification improvement. NASA will facilitate interaction between selected teams and user communities that can eventually utilize methods for reducing geomagnetic storm-time upper atmosphere densities in satellite drag applications. The use of density databases not readily available to the scientific community at the present should explored, and processes identified, to make these types of data more widely available.